

Aerodynamic Parameters for a Sparsely Roughened Surface Composed of Small Cotton Plants and Ridged Soil

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Roughness length (z_0) and displacement height (d_0) parameters are required in most algorithms that use remotely sensed data to estimate sensible heat and latent heat fluxes at the earth's surface. Estimates of aerodynamic roughness parameters often have large uncertainties, particularly for sparsely-roughened surfaces, such as agricultural row crops early in the growing season. The purpose of this study was to use wind profile data collected at four levels under near-neutral conditions to estimate z_0 and d_0 for small cotton plants (mean plant height ≈ 0.31 m) growing on 0.16 m high soil ridges in Arizona. Four 24-min periods with near-neutral conditions and wind direction perpendicular to the rows were identified over two days in June 1988. From these periods, a mean $z_0 \approx 0.02$ m and a mean $d_0 \approx 0.23$ m were determined. Relative to total obstacle height (h = plant height + ridge height), these values correspond to $z_0/h \approx 0.04$, and $d_0/h \approx 0.50$, which differ considerably from previously published values for partial canopy cotton.

INTRODUCTION

An important application of remote sensing information is in the evaluation of the energy and water budgets of natural and agricultural land surfaces (e.g., Soer, 1980; Gurney and Camillo, 1983; Jackson et al., 1987). Particular focus has been placed on obtaining reliable estimates of evapotranspiration (ET) at various spatial and temporal resolutions. This is because the magnitude of ET relative to other components of the surface energy and water budgets has important implications in modeling a wide range of geophysical processes (e.g., Clothier, 1988; Rabin et al., 1990). A common method is to solve for latent heat flux density (LE , $W\ m^{-2}$) as a residual in the surface energy balance equation, i.e.,

$$LE = -[R_n + G + H], \quad (1)$$

where L is the heat of vaporization ($J\ kg^{-1}$), E is the water vapor mass flux density ($kg\ m^{-2}\ s^{-1}$), R_n is the net radiation ($W\ m^{-2}$), G is the soil heat flux density ($W\ m^{-2}$), and H is the sensible heat flux density ($W\ m^{-2}$). [Fluxes directed away from the surface are assigned a negative value in Eq.

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(1)]. Significant progress has been made in evaluating R_n and G (e.g., Jackson et al., 1985; Clothier et al., 1986; Kustas and Daughtry, 1990) using primarily remotely sensed data. However, in evaluating H (e.g., Hatfield et al., 1984), parametrization of the turbulent transfer processes using remote sensing information has not been very successful because of the strong dependence on local meteorological conditions and aerodynamic properties of the surface. This is seen by considering the bulk resistance expression for transport of H across the surface-atmosphere interface (Monteith, 1973):

$$H = \rho c_p \frac{[T_a - T_s]}{r_{ah}}, \quad (2)$$

where ρ is the density of air (kg m^{-3}), c_p is the specific heat of air at constant pressure ($\text{J kg}^{-1} \text{K}^{-1}$), T_s is the surface temperature (K) (typically measured by infrared thermometry), T_a is air temperature (K), and r_{ah} is a stability corrected aerodynamic resistance (s m^{-1}) to sensible heat transport which is normally expressed using Monin-Obukhov surface layer similarity (Brutsaert, 1982):

$$r_{ah} = \frac{\{\ln[(z - d_0)/z_0] - \Psi_m\} \times \{\ln[(z - d_0)/z_{0h}] - \Psi_h\}}{k^2 u}. \quad (3)$$

The height (z, m) above the surface is where horizontal wind speed ($u, \text{m s}^{-1}$) and T_a are measured, while the roughness lengths for sensible heat (z_{0h}, m) and momentum (z_0, m), and the displacement height (d_0, m) are properties of the surface. The Ψ_m and Ψ_h are stability correction factors for momentum and sensible heat, respectively, which are functions of the Monin-Obukhov stability parameter [ζ given by Eq. (8)], and k ($= 0.4$) is von Karman's constant. Although the environmental parameters (i.e., wind speed and temperature) can be measured directly, the aerodynamic parameters (z_{0h} , z_0 and d_0) must generally be estimated based on knowledge of the vegetation type and roughness characteristics of the land surface (Brutsaert, 1982). Also, to evaluate Eq. (3), it is often assumed that z_{0h} is a constant fraction of z_0 (Choudhury et al., 1986). Thus, evaluation of r_{ah} [and H from Eq. (2) and LE from Eq. (1)] becomes mainly a problem of accurate estimation of z_0 and d_0 . In some instances, small uncertainties in one or both of these parameters may lead to large uncertainties

in estimated surface fluxes. Flux estimates may be particularly sensitive to the uncertainties in these parameters for surfaces with sparse plant canopies (e.g., Kustas et al., 1989b), such as cropped surfaces early in the growing season.

Both z_0 and d_0 may be determined from micrometeorological measurement of the wind speed profile within the dynamically neutral inertial sublayer. However, because of experimental complexities associated with wind profile measurements, much field and laboratory research has been done to relate both z_0 and d_0 to more easily measured geometric properties of the surface, such as the mean height of the surface roughness obstacles (e.g., Stanhill, 1969; Szeicz et al., 1969), the frontal area of and spacing between the obstacles (e.g., Lettau, 1969; Seginer, 1974; Raupach et al., 1980), and the fraction of the total surface area covered by rigid roughness elements of known height (e.g., Abtew et al., 1989). In addition, recent research (Susan Moran, personal communication, 1990) has shown considerable potential for relating z_0 and d_0 to vegetation index values derived from remotely sensed multispectral data.

In field studies done over uniform cover, z_0 has generally been found to be a relatively constant fraction (of order 0.1) of the mean height (h) of the roughness obstacles. Similarly, d_0 has been determined to be about 2/3 of h . However, as discussed by Lettau (1969) and others, height-based empirical relationships fail to predict differences in parameters among sites with obstacles having identical heights but differing spatial distributions. Recent research by Hatfield (1989) with small cotton plants in Texas indicates that estimates of z_0 and d_0 based on these simple fractions of height may, indeed, give erroneous values for partial cover crops. In fact, Hatfield (1989) showed that, for cotton of intermediate foliage density, z_0 became nearly 0.8 of the mean crop height.

The experimental results by Hatfield (1989) for the variation in z_0 are in qualitative agreement with earlier studies done in wind tunnels with arrays of obstacles such as rods or slats [for compilation of wind tunnel results, see, Seginer (1974; Fig. 1)]. It is also qualitatively in agreement with mixing-length based model calculations by Seginer (1974; see Fig. 2), and the second order closure model by Shaw and Pereira (1982). The model by Seginer indicates that normalized z_0 (i.e., z_0/h)

is not constant (e.g., 0.13), but rather varies with the product of the drag coefficient (C_d) for the individual roughness elements, the area of elements per unit air volume (A_f, m^{-1}), and the height (h, m). The Segner model indicates that z_0/h is near zero for small ($C_d A_f h$) (i.e., sparsely-placed obstacles) and increases with increasing ($C_d A_f h$) to a maximum at $(C_d A_f h) \approx 0.1-0.2$. This value, however, as pointed out by Shaw and Pereira (1982), depends primarily on the manner in which the mixing length is described. Therefore, they caution the use of mixing-length model results in determining z_0/h and d_0/h for all surface types. Beyond about 0.2, the z_0/h ratio should, according to Segner (1974, see Fig. 2), gradually decrease. Brutsaert (1982) interpreted the unimodal variation in z_0/h on the basis that as the density of the sparsely-placed obstacles increases, z_0 will increase due to increased drag. But with very small spacing between obstacles, little penetration of air flow between the obstacles will occur, thus decreasing drag and z_0 .

Kustas et al. (1989a) reported that for a partial cover of small cotton plants (height ≈ 0.31 m) growing on soil ridges, z_0 and d_0 were about 0.13 and 0.67 of total height ($h \approx 0.5$ m), respectively. Their results obtained at the University of Arizona Maricopa Agricultural Center (field no. 28) during early June 1987 show good agreement with the simple height-based empirical model predictions, but differ from Hatfield's results for cotton plants with comparable heights (≈ 0.3 m) and growing on ≈ 0.1 m tall soil ridges. Hatfield's (1989) Table 1 equations indicate z_0 and d_0 would be about 0.34 and 0.35 of total height ($h \approx 0.4$ m), respectively.

In light of the dissimilar results reported by Hatfield (1989) and Kustas et al. (1989a), we have analyzed our own wind profile data collected over small cotton (field no. 28 at the Maricopa Agricultural Center) in early June 1988. The purpose of this paper is to report calculated values of z_0 and d_0 and to qualitatively compare these with modeled and measured values from the literature.

MATERIALS AND METHODS

Site, Instrumentation, and Data Collection

Environmental measurements were made during June 1988 over irrigated cotton (*Gossypium hirsu-*

tum L. cv. Delta Pine 77) in field no. 28 at the University of Arizona Maricopa Agricultural Center (MAC) (longitude 111.98 W, latitude 33.07 N, elevation 366 m). The field was approximately 1600 m long (in the east–west direction) by 275 m wide. Instruments were setup approximately 90–100 m from the north edge and 500 m from the east edge of the field. Fetch, therefore, was a minimum of about 90 m for northerly winds, and increased to about 1100 m for westerly winds. Surrounding irrigated fields were of roughness similar to the cotton field, except for a mature pecan orchard directly west of the field. Prevailing winds during daylight hours tended to be within a southwest to northwest sector.

Cotton planting date was 29 March 1988, and emergence occurred on 5 April 1988. Row orientation was north–south. Row width was 1 m. Ridge (i.e., furrow bed) height was about 0.16 m. The soil surface within the furrow was relatively smooth due to compaction by surface irrigation. The surface was dry and had not been recently cultivated in the vicinity of the instrumentation. Plant height and area data collected in the vicinity of the instruments were as follows: plant density was about $11.8 \text{ plants m}^{-2}$, biomass was 58 g m^{-2} , leaf area index was 0.42, average plant height was about 0.31 m, and ground cover averaged 20%. Total crop height (h , plant + ridge) was about 0.47 m. No flowers or bolls were observed. In contrast to plant data collected near the instruments, there was a sparser stand and smaller plants in the west half of the field. MAC records indicate that a 2 ha area in the middle portion of the field (approximately 300 m west of the instruments) was replanted 14 April 1988 because initial emergence of plants was poor. In fact, in the replanted area, plant density averaged only $7.6 \text{ plants m}^{-2}$, biomass was 24 g m^{-2} , leaf area index was about 0.18, average plant height was about 0.21 m (total crop height was about 0.37 m), and ground cover was about 11%.

Deviations from the mean vertical wind speed ($w', \text{m s}^{-1}$) were measured with a single-axis Campbell Scientific Inc.¹ (CSI) Model CA27T

¹Trade names and company are given for the benefit of the reader and do not imply endorsement of the product or company by the organizations with which the authors are affiliated.

continuous, switched-wave sonic anemometer (Campbell and Unsworth, 1979). Deviations from mean air temperature (T' , °C) were measured with a CSI 13- μ m, type E, fine-wire thermocouple attached to the CA27T and placed 0.03 m from the 0.1 m acoustic path length. The CA27T sensors were placed directly above a cotton row at a height of 1.4 m above the bottom of the furrow. Sensors were oriented toward the southwest. Output signals were sampled at 0.2-s intervals by a CSI 21X Micrologger and processed over a 12-min period to yield a $w'T'$ covariance value for use in calculation [Eq. (4)] of sensible heat flux density (H) by eddy correlation. Values of H were used in determining periods with near-neutral stability conditions. Output signals from the CA27T were sampled from 1024 MST on 10 June [day of year (DOY) 162] through 1024 MST on 16 June (DOY 168).

An energy balance Bowen ratio system (Gay, 1988) with two interchangeable psychrometers, a net radiometer, and two soil heat flux disks was installed slightly north of the CSI CA27T sensors. This system provided an evaluation of latent heat flux density (LE) at 12-min intervals, and operated concurrently with the CA27T sensors. Values of LE were used in determining periods with near-neutral stability conditions. The psychrometers were separated vertically by about 1 m. The lower psychrometer was placed about 0.45 m above a soil ridge. The net radiometer was positioned 1.68 m above the ridge. The heat flux disks were connected in parallel to yield an estimate of the mean soil heat flux density. One disk was buried at 0.01 m beneath a cotton row, and the other at 0.01 m depth in the middle of a furrow.

Horizontal wind speed (u , m s⁻¹) was measured with four Qualimetrics Model 2032 micro-response cup anemometers (reed switch with threshold speed about 0.23 m s⁻¹) positioned at each of four heights (z , m) on a mast. The mast and anemometers were placed midpoint between two rows. Each anemometer was supported on an arm directed south from the mast. Referenced from $z = 0$ at the bottom of the furrow, the wind speed measurement heights were $z_1 = 0.48$ m, $z_2 = 0.97$ m, $z_3 = 1.50$ m, and $z_4 = 2.16$ m. Wind direction (WD, expressed in degrees clockwise from north) was measured with a Metone Model 024A windvane positioned 0.9 m above the furrow.

Table 1. Linear Regression Results Comparing 12-Min Average u Values from Four Qualimetrics Model 2032 Anemometers Positioned at the Same Height

y	x	Slope	Intercept (m s ⁻¹)	r^2	n
u_2	u_1	0.978	0.076	0.9978	708
u_3	u_1	0.983	0.046	0.9956	708
u_4	u_1	0.990	0.062	0.9970	708
u_3	u_2	1.004 ^a	-0.030	0.9962	708
u_4	u_2	1.010	-0.013	0.9966	708
u_4	u_3	1.004 ^a	0.020	0.9964	708

^aslope = 1 at $\alpha = 0.05$ level.

Wind speed and wind direction signals were sampled at 20-s intervals with averages (and standard deviation of wind direction) calculated by the CSI 21X over a 12-min period. Signals were sampled from 1024 DOY 162 through 1024 DOY 168. Linear regression results given in Table 1 indicate good statistical agreement among the four anemometers when placed at the same height (1.5 m) for about 1 week.

Eddy Correlation Measurement of Sensible Heat Flux Density

The one-dimensional eddy correlation method determines vertical turbulent sensible heat flux density (H , W m⁻²) from

$$H = \rho c_p \overline{w'T'}, \quad (4)$$

where ρ is the air density (kg m⁻³), c_p is the specific heat of air (J kg⁻¹ K⁻¹), and w' and T' are instantaneous deviations from the time averaged vertical wind speed and air temperature, respectively. The overbar denotes a time average (12 min) of the products of the w' and T' deviations sampled at 0.2-s intervals.

Formulation of H according to Eq. (4) assumes that mean w is zero. Because of sensor misalignment, distortion of airflow by instrument or mast, and/or other causes (see Kraan and Oost, 1989), mean w may not always be zero. Measurements of 12-min mean w made with the CSI CA27T over the cotton revealed slight departures from zero throughout each day, which introduced uncertainty in the calculated H values. Uncertainty in T' (and H) values may also arise due to varying thermal mass reference temperature of the CSI CA27T pivot arm in response to varying solar radiation (Gaynor and Biltoft, 1989).

Additional uncertainty in H is due to inadequate frequency response of the CSI CA27T. Moore (1986) developed a procedure to correct for the frequency response loss in sensible heat flux measurement by eddy correlation systems. Moore showed that typical flux loss is about 5%, but will vary with factors such as atmospheric stability, sensor height, and wind speed [see Fig. 5 in Moore (1986)]. Given the specifications of the CSI CA27T instrument and its height above the apparent zero plane displacement, a 5% correction to the H values would not be unreasonable. However, given the uncertainty in the corrections, we have chosen to simply use the uncorrected values of H .

Measurement of Evaporation Flux Density by the Energy Balance Bowen Ratio Method

The effect of water vapor on buoyancy and thus stability was accounted for by direct measurements of evaporation using the energy balance Bowen ratio method (Gay, 1988). Evaporative mass flux density (E) was computed from

$$E = \frac{-(R_n + G)}{L(1 + \beta)}, \quad (5)$$

where β is the Bowen ratio. The ratio is given as

$$\beta = \frac{c_p (T_2 - T_1)}{L (q_2 - q_1)}, \quad (6)$$

where T is dry-bulb air temperature (K) and q is specific humidity (kg kg^{-1}). Here, subscripts 2 and 1 refer to upper and lower psychrometers, respectively.

Estimation of Aerodynamic Roughness Parameters

Under near-neutral conditions mean horizontal wind speed (u) was assumed to be a function of the logarithm of the height (z) within the inertial sublayer above the surface. This function is given as

$$u = \frac{u_*}{k} \ln \frac{z - d_0}{z_0}, \quad (7)$$

where u_* [$\equiv (\tau/\rho)^{1/2}$] is the friction velocity (m s^{-1}), τ is the surface shear stress (Pa), k is the nondimensional von Karman constant (0.4), z_0 is

the roughness length (m) for momentum, and d_0 is the zero plane displacement height (m). The d_0 is a fitting parameter whose physical significance is somewhat uncertain (see De Bruin and Moore, 1985). However, from Thom (1971) d_0 may be interpreted as representing the mean level of momentum absorption by the surface roughness elements. The z_0 parameter represents the distance above d_0 at which the logarithmic wind profile extrapolates to zero.

Equation (7) is not valid below the lower limit of the inertial sublayer. Below that limit, a transition (surface roughness) layer exists in which the air flow is directly influenced by wake effects and horizontal inhomogeneities due to individual roughness elements. Previous research with relatively tall vegetation indicates that the height of the lower limit of the inertial sublayer is dependent on several geometrical parameters including the size, shape, and frontal area of the elements, and the spacing between the elements (e.g., Garratt, 1978; Raupach et al., 1980). Raupach et al. (1980) concluded that for application of conventional turbulent diffusion theory the lowest measurement height should exceed $(h + 1.5D)$, where h is the mean height of the roughness elements and D is the inter element spacing. Application of this criteria in the present study with $h = 0.47$ m and $D \approx 0.7$ m (approximate spacing between cotton rows) would indicate that the lower limit was about 1.5 m, which is above the two lowest anemometers. If the depth of the roughness sublayer includes the lowest two anemometers, then the wind profile data would produce an underestimate of d_0 (Raupach et al., 1980).

Estimation of u_* , d_0 , and z_0 (the latter two parameters to within ± 0.1 mm) in Eq. (7) was done by application of an iterative least square errors technique (Robinson, 1962; Kustas et al., 1989a) to the wind speed profile data collected during near-neutral (adiabatic) conditions. Comparison among various techniques by Azevedo and Verma (1986) for estimating z_0 and d_0 suggest the iterative technique should give reliable estimates. However, more recent evidence casts some doubt on this approach (Jacobs and van Boxel, 1988).

Similar to Dolman (1986) and others, analysis of environmental data to compute aerodynamic parameters was done using values averaged over

24 min. Local time values given in this paper denote the midpoint of the 24-min period. Reasonably stringent criteria were used to select appropriate wind speed input data for estimation of aerodynamic roughness parameters with near neutral atmospheric conditions. These criteria (a.–f.) are as follows:

- a. Mean wind direction (WD) could not vary by more than 20° from one 24-min period to the next period. This imposed near stationarity of wind direction.
- b. Mean wind direction could not exceed $\pm 30^\circ$ from due west. This limited data to periods with a fetch of about 1100 m, which should have placed the upper anemometer (≈ 1.7 m above cotton plants) within the fully adjusted inertial sublayer.
- c. Period to period variation in mean wind speed (average of all four levels) $< 15\%$. This stationarity requirement restricted data to runs with relatively steady wind speed conditions.
- d. Lowest level wind speed $u_1 > 1 \text{ m s}^{-1}$; this restricted use of data to periods in which wind speed at the lowest level was at least four times the threshold (startup) speed of the three-cup anemometer.
- e. The measured sensible heat flux density $|H| < 15 \text{ W m}^{-2}$; this criterion was slightly less stringent than that suggested by Hicks et al. (1989) and was used to select data collected under possible near-neutral conditions. If all criterion (a)–(e) were met, then d_0 , z_0 , and u_* were calculated iteratively from Eq. (7).
- f. The Monin–Obukhov stability parameter $|\zeta| \leq 0.015$; The parameter (ζ) calculated from Eqs. 8 and 9 (with estimated u_* and d_0 from Eq. (7), and measured H , E , T_a inputs) was used to infer if near-neutral conditions occurred on average during a 24-min run.

The Monin–Obukhov stability parameter (see Brutsaert, 1982, p. 65) was calculated from

$$\zeta = \frac{z_r - d_0}{L_0}, \quad (8)$$

where z_r is a reference height and L_0 is the Obukhov stability length defined as

$$L_0 = \frac{u_*^3 \rho}{kg[H/T_a c_p + 0.61E]}. \quad (9)$$

In Eq. (9), g is the acceleration due to gravity (9.8 m s^{-2}), T_a is the air temperature (K) at z_r , and E is the water vapor mass flux density ($\text{kg m}^{-2} \text{ s}^{-1}$). Both T_a and E were measured by the energy balance Bowen ratio method. T_a was calculated as the mean of the dry-bulb temperatures measured by the psychrometers at the two levels. The height $z_r \approx 1 \text{ m}$ was taken as the arithmetic mean of z_1 and z_3 . With both H and E assigned a negative value if directed away from the surface, ζ is positive for stable, negative for unstable, and zero for neutral conditions. An $|\zeta| \leq 0.015$ was considered sufficiently close to zero to indicate neutral conditions. With $z_r - d_0 \approx 0.7 \text{ m}$, this criterion corresponds approximately to an $|L_0| \geq 50 \text{ m}$. The ± 0.015 range for ζ is approximately equivalent to the ± 0.015 range for the Richardson number used by Kustas et al. (1989a), and is somewhat more stringent than the ± 0.1 Richardson number range used by Hatfield (1989) to identify near-neutral conditions over partial canopy cotton.

RESULTS

Calculated z_0 , d_0 , and u_*

Four 24-min periods with near-neutral conditions were identified using the previously described criteria. These periods occurred in the late afternoon on days 162 and 163. Measured mean environmental input data collected during each of the four selected periods are summarized in Table 2. Of the four periods, wind directions were nearly from the west ($\text{WD} \approx 280^\circ$) with fetch of about 1100 m. Wind speeds were moderate and relatively constant ($\approx 2 \text{ m s}^{-1}$) from day to day.

Calculated values of ζ , d_0 , z_0 , and u_* for each period are given in Table 3 along with overall mean values ± 1 standard deviation. The overall mean d_0 and mean z_0 values calculated using all four levels of wind speed were 0.234 m ($\pm 0.033 \text{ m}$) and 0.021 m ($\pm 0.004 \text{ m}$), respectively. The range in d_0 and z_0 values were relatively small. The coefficient of variation (CV) about the mean for both z_0 and d_0 was comparable to Hatfield (1989), who found CVs of less than 10% using data from a minimum of five 15-min (near-neutral) intervals per day.

There were also two cases of near-neutral profiles with predominantly southerly flow. The aero-

Table 2. Mean Environmental Input Data during Each of Four Selected 24-Min Periods with Near-Neutral Conditions

DOY	Time	u_1	u_2 ($m\ s^{-1}$)	u_3	u_4	WD (deg)	H ($W\ m^{-2}$)	LE ($W\ m^{-2}$)	T_a ($^{\circ}C$)
162	1724	1.16	1.73	1.98	2.19	274	12.1	-131	36.8
163	1636	1.76	2.49	2.86	3.16	280	-10.4	-219	37.2
163	1700	1.51	2.18	2.52	2.78	291	2.1	-173	36.7
163	1724	1.71	2.48	2.87	3.18	278	13.3	-164	36.4

Table 3. Values of ζ , d_0 , z_0 , and u_* Calculated Using All Four Levels of Wind Speed Measured during Four Selected 24-Min Periods with Near-Neutral Conditions

DOY	Time	ζ	d_0 (m)	z_0 (m)	u_* ($m\ s^{-1}$)
162	1724	0.002	0.281	0.015	0.18
163	1636	-0.011	0.207	0.022	0.28
163	1700	-0.007	0.231	0.021	0.25
163	1742	0.0004	0.218	0.025	0.29
Mean			0.234	0.021	0.25
S.D.			± 0.033	± 0.004	± 0.05

dynamic parameters determined by these two profiles gave a mean $d_0 \approx 0.11$ m (± 0.1 m) and a mean $z_0 \approx 0.05$ m (± 0.02 m). These results suggest that the parameters are markedly different for flow along the rows. However, due to the lack of more data and also fetch constraints (i.e., less than 200 m fetch in the southerly direction) quantifying the change in z_0 and d_0 due to wind direction is not possible with the present data set.

DISCUSSION

The results of this study and conflicting findings from some recent investigations (Hatfield, 1989; Kustas et al., 1989a) suggest that the profile technique has severe limitations for estimating the roughness parameters. Previous work (e.g., Legg and Long, 1975; Maki, 1975) has shown that z_0 and d_0 are strongly correlated, and hence a unique mathematical solution for both parameters cannot be obtained. More recently, Jacobs and van Boxel (1988), using wind profile data and the eddy correlation technique, showed that z_0 and d_0 varied over the course of a day. In practice, wind profile data and sonic anemometers are rarely available for determining the roughness parameters over various surfaces. As a result, for many practical applications an estimate of z_0 and d_0 must come from the literature.

In order to combine the results of various studies of the roughness parameters for cotton, a dimensionless relationship between z_0 and d_0 was used (Shaw and Pereira, 1982), i.e.,

$$\frac{z_0}{h} = C \left[1 - \frac{d_0}{h} \right], \quad (10)$$

where C is a proportionality factor. Although mixing-length and second-order closure models show that this relationship is applicable only for a dense crop, measurements by Jacobs and van Boxel (1988; Fig. 4) suggest Eq. (10) may be a reasonable first-order approximation over the whole growth cycle for some plant species (i.e., corn). Moore (1974) determined C to be of order 0.26 (± 0.07) for vegetation ranging from grasses to forest while the numerical experiments of Segner (1974) and Shaw and Pereira (1982) found $C = 0.28$ and 0.29 , respectively. In addition, Abtew et al., (1989) compiled observations from the literature to determine $C = 0.13$ for roughness elements ranging in size from sand grains to 20 m tall trees.

For cotton, the experimental findings of Stanhill and Fuchs (1968) as well as the findings of Kustas et al. (1989a) and the present study are plotted according to Eq. (10) in Figure 1. Also given in Figure 1 are the least squares fit of the Stanhill and Fuchs data ($C = 0.21 \pm 0.01$; $R^2 = 0.5$) and the relationship determined by Shaw and Pereira (1982). The Kustas et al. (1989a) result is slightly greater than the data from Stanhill and Fuchs (1968), whereas the estimate from the present study seems to fall markedly below these curves and other data. But it could be argued that the roughness elements in the present study were sparse enough that the value should fall away from the linear relationships given by Eq. (10). It should also be pointed out that the cotton crops in the Stanhill and Fuchs (1968) study did not contain sizeable furrows nor was there a significant number of measurements made at the lower plant density. It is also worth noting that $C = 0.09$ for

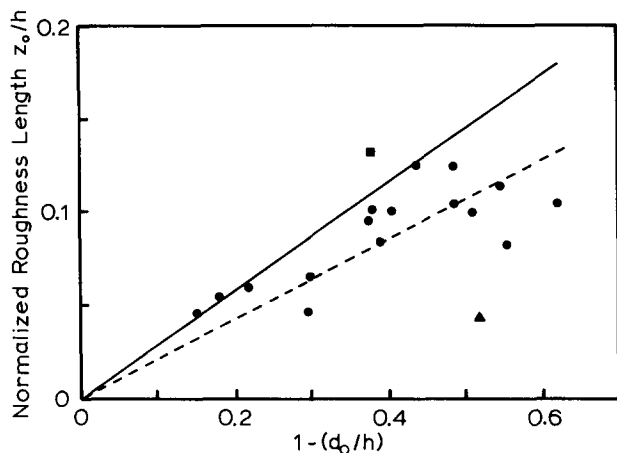


Figure 1. Plots of z_0/h versus $1 - (d_0/h)$ based upon data from Stanhill and Fuchs (1968) (●), Kustas et al. (1989a) (■), and the present study (▲): (---) least squares fit to the Stanhill and Fuchs (1968) data; (—) relationship determined by Shaw and Pereira (1982).

the present study is in reasonably close agreement with the general result (i.e., $C = 0.13$) determined by Abtew et al. (1989).

The differences in results among the various studies illustrated in Figure 1 are rather small when compared with the relationship between z_0/h and $[1 - (d_0/h)]$ developed from regression equations determined by Hatfield (1989) for estimating z_0 and d_0 as a function of the height to row width ratio [see Table 1 in Hatfield (1989)]. The relationship between z_0/h and $[1 - (d_0/h)]$ from Hatfield is shown in Figure 2 along with the data from Figure 1. Clearly, the equations from Hatfield (1989) for computing z_0 and d_0 yield

Figure 2. Plots of z_0/h versus $1 - (d_0/h)$ based upon data from Stanhill and Fuchs (1968) (●), Kustas et al. (1989a) (■), and the present study (▲): (—) derived from equations given by Hatfield (1989, Table 1)

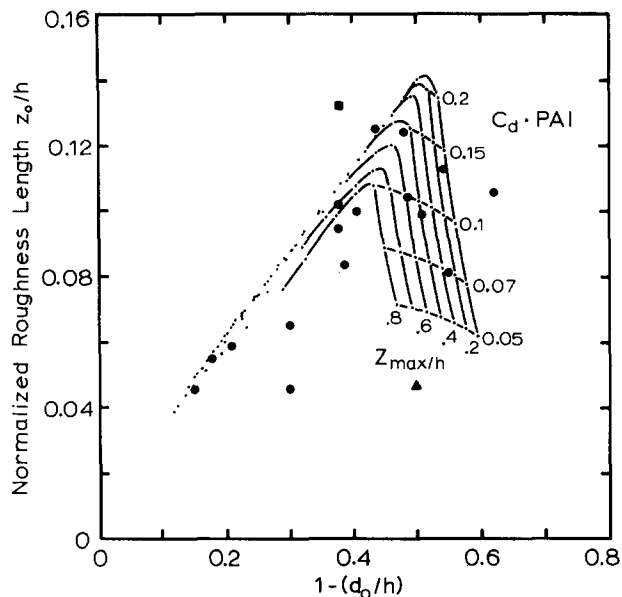
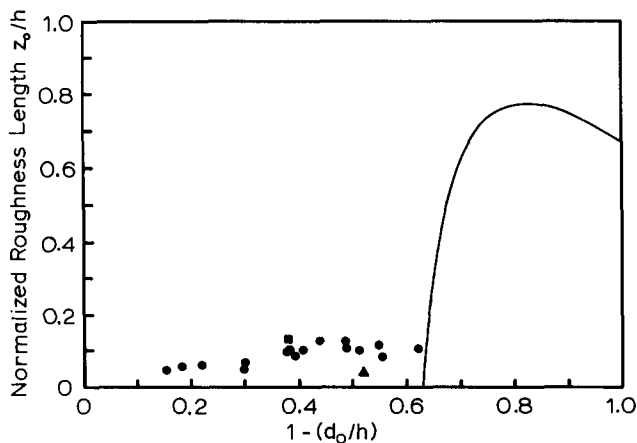


Figure 3. Plots of z_0/h versus $1 - (d_0/h)$ based upon data from Stanhill and Fuchs (1968) (●), Kustas et al. (1989a) (■), and the present study (▲). The family of curves is redrawn from Shaw and Pereira (1982; see Fig. 6), which illustrates simulated results for a range of C_d PAI and z_{\max}/h . From Shaw and Pereira (1982), z_{\max} represents the level at which maximum plant area density occurs.

different estimates from those by Stanhill and Fuchs (1968), Kustas et al. (1989a), and the present study.

As a final comparison, the observations of Stanhill and Fuchs, Kustas et al., and the present study are plotted against the simulation results of Shaw and Pereira (1982; Fig. 6) in Figure 3. Both the observations given by Kustas et al. (1989a) and the present study lie somewhat outside the family of curves; however, the scatter in the observations by Stanhill and Fuchs (1968) would not preclude rejecting either finding. Still, the result from the present study appears to be suspect because none of the simulations, even at very low vegetation densities (i.e., C_d PAI = 0.05, where PAI is plant area index), suggest for $\{1 - (d_0/h) \approx 0.5\}$ that z_0/h be on the order of 0.04. This may reflect possible roughness sublayer effects on the estimated d_0 and z_0 values with the data from the present study. On the other hand, observations from Azevedo and Verma (1986; Fig. 2, 1983 data) for a sparse cover of sorghum suggest that $z_0/h \approx 0.04$ along with $\{1 - (d_0/h) \approx 0.5\}$ can exist.

As a means of testing the hypothesis that roughness sublayer effects influence calculated roughness parameter values, wind speeds from the

Table 4. Values of z_0 Calculated from Eq. (7) (with Values of d_0/h Assumed) Using Only the Upper Two Levels of Wind Speed Measured during Four Selected 24-Min Periods with Near-Neutral Conditions^a

DOY	Time	z_0		
		$d_0/h = 0.67$	$d_0/h = 0.49$ (m)	$d_0/h = 0.38$
162	1724	0.020	0.027	0.032
163	1636	0.018	0.025	0.030
163	1700	0.014	0.020	0.024
163	1724	0.020	0.027	0.032
Mean		0.018	0.025	0.029
S.D.		± 0.003	± 0.003	± 0.004

^aObstacle height $h \approx 0.48$ m.

upper two anemometers were used in Eq. (7) to obtain exact solutions for z_0 based upon three different d_0 values. The d_0 values were arbitrarily selected in order to represent a wide range of possible values. Expressed as a fraction of total crop height (h), these values were $d_0/h \approx 0.38$, 0.49, and 0.67. Calculated z_0 values were found to be relatively insensitive to d_0 (Table 4). The good agreement among z_0 values calculated from only the two upper levels (Table 4) and z_0 values calculated from all four levels (Table 3) suggests that the roughness sublayer effects have only minimal effect on the estimated roughness parameters. This agreement is also consistent with Jacobs and van Boxel (1988), who defined the upper limit of the roughness sublayer as $d_0 + 10z_0$. According to their definition, our lowest anemometer at $\{z_1 = 0.48 \text{ m}\}$ was slightly above $\{d_0 + 10z_0 = 0.44 \text{ m}\}$.

Another important observation shown in Figure 3 is that the Stanhill and Fuchs (1968) data, which fall along the linear segment around $\{1 - (d_0/h) \approx 0.2\}$, are actually given by the partial canopy cover conditions instead of the expected dense cover situation used to derive Eq. (10). A plausible explanation may be that under near-neutral conditions vorticular flow may be produced within cavities in open row crop canopies when the mean flow field above the canopy is perpendicular to the rows (Arkin and Perrier, 1974). Under these conditions, there may be appreciable decoupling of the flow field above the canopy from the vorticular flow within the row cavities. This would suggest a condition where Eq. (10) is applicable, namely, the flow field above the canopy would behave as if the underlying surface was composed of a dense arrangement of obstacles.

This decoupling of the flows above and within structured (but open) canopies would tend to increase z_0 and d_0 relative to those for sparsely-roughened surfaces in which decoupling of flows is less likely to occur.

Since the major impetus for this study was to evaluate the aerodynamic parameters of an evapo-transpiration model [i.e., Eqs. (1)–(3)] that incorporates remote sensing information, a sensitivity analysis was done of the variation in the computed value of H [Eq. (2)] due to a possible range in the estimated roughness parameters. To do the analysis, we used the z_0 and d_0 values from Kustas et al. (1989a) and from the present study. We used these values because the furrow dimensions and vegetation properties in both studies were similar, yet markedly different values were obtained, i.e., $z_0/h \approx 0.1$ and $d_0/h \approx 0.7$ in the Kustas et al. (1989a) study, and $z_0/h \approx 0.04$ and $d_0/h \approx 0.5$ in the present study. Given environmental conditions where $T_a - T_s \approx -5 \text{ K}$ and $u \approx 2 \text{ m s}^{-1}$, then Eq. (3) [using $z_{0h} = 0.1z_0$, and Ψ_m and Ψ_h approximated with an approach given by Kustas et al. (1989b)] yields r_{ah} values of approximately 20 s m^{-1} and 40 s m^{-1} for the Kustas et al. (1989a) study and the present study, respectively. As a result, the values of H computed from Eq. (2) with $T_a - T_s \approx -5 \text{ K}$ and $\rho c_p \approx 1000 \text{ J m}^{-3} \text{ K}^{-1}$ are -250 W m^{-2} and -125 W m^{-2} for the Kustas et al. study and the present study, respectively. Clearly, this difference in H between the two studies will result in a similar difference in LE [calculated from Eq. (1)], which is unacceptable for many applications. For example, for typical midday conditions where $R_n + G \approx 500 \text{ W m}^{-2}$, the LE estimate would range between -250 W m^{-2} and -375 W m^{-2} for the two studies. This would also correspond to a range in the Bowen ratio (β) value from 1 to 0.3.

CONCLUSIONS

The analysis of the present data and comparison with several other studies over cotton suggest that values of z_0 and d_0 are highly variable especially under partial canopy cover conditions. This can lead to large variations in H and LE computed from Eqs. (2) and (1), respectively. Both parameters appear to be sensitive to plant height and density. Moreover, the effect of the shape and size

of the underlying soil surface roughness elements on the calculated parameters also needs careful field study. Some of the disagreement in z_0 and d_0 estimates as a function of obstacle heights among the various studies considered here may be due to wind speed measurements taken inside the roughness sublayer, and the fact that u_* , d_0 , and z_0 were all determined with one equation [i.e., Eq. (7)], which may lead to erroneous results (e.g., Jacobs and van Boxel, 1988). Consequently, an independent measurement of u_* , such as with eddy correlation, would provide a means of obtaining unique values of z_0 and d_0 .

It is worth noting that in the present study the density, size, and leaf area index of the cotton crop for approximately the first 800 m of the 1100 m fetch were smaller than for the crop near the profiling instruments. Thus, it is conceivable that the estimated z_0 and d_0 may reflect to some degree the smaller aerodynamic roughness conditions upwind. Furthermore, due to patchiness in crop cover in the first 800 m, gaps of bare soil on the furrow beds were prevalent, creating a nonuniform row structure; this may have prevented a decoupling of the flow field as observed by Arkin and Perrier (1974), and as a result the deviation from results of previous studies illustrated in Figure 1. In particular, this may help explain why Kustas et al. (1989a), found larger parameter values in June 1987 when MAC field 28 had a more uniform surface cover than it did during our present study in June 1988.

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